Sound Speed and Attenuation in Multiphase Media

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LONG-TERM GOALS

One research goal developed from conducted shallow water (SW) acoustic transmission experiments in sandy-silty areas [1] revealed a nonlinear power law frequency-dependent attenuation at lower frequencies (≤ 1 kHz) consistent with results reviewed in [2-5] and the observations by the ONR-HEP program. The Biot Theory [6] predicts that the sandy- sediment frequency-dependent attenuation should be quadratic, $\alpha(f) = \alpha(f_o)(f/f_o)^n$ with $n = 2$; however the observed dependence was $n = 1.8 \pm 0.2$. Thus the long-range goal was to develop a simplified theory of sediment attenuation [7] verified by measurements that could explain this dependence and be applied to ocean sediments.

OBJECTIVE

The objective of the work was to determine the frequency dependent attenuation and phase speed characteristics of selected sandy sediments (both water saturated and partially saturated) at the lower frequencies to verify a simplified Biot theory] and to provide a theoretical / experimental basis for the water-sediment boundary condition necessary for the accurate prediction of wide band transmission loss in shallow waters.

APPROACH

This work was aimed at enhancing our understanding of saturated and partially saturated sandy sediment for frequencies ranging from 100 Hz to 10 kHz. The basic hypothesis is based on the simplified Biot sediment theory [7] and the prediction that high permeability sands will have a quadratic frequency dependent attenuation, and that these measure-ments can be described by a Biot time constant. Previously, the Nantucket Sound Experiment, have been [8,9] we compared this theory to experimental results from an experiment with known environmental (isospeed) conditions, geophysical properties, surface roughness and water depth. While the theory predicts a power-law dependence with an exponent of $n = 2$; results from this experiment agreed with other experiments conducted under similar conditions yielded an exponent on average of approximately

$$\alpha(f) = \alpha(f_o)\cdot(f/f_o)^n;\ \ with\ \ 0.261 \leq \alpha(1\ kHz) \leq 0.273\ and\ n = 1.87^{+0.17}_{-0.21}.$$

This compares with a summary by Zhou [2] drawn from a larger and less restrictive group of experimental results yielded $\alpha(f_o) = 0.34; n = 1.84$ is consistent with the measurements of Hamilton [10] at 1 kHz.

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14. ABSTRACT
One research goal developed from conducted shallow water (SW) acoustic transmission experiments in sandy-silty areas [1] revealed a nonlinear power law frequency-dependent attenuation at lower frequencies (≤ 1 kHz) consistent with results reviewed in [2-5] and the observations by the ONR-HEP program. The Biot Theory [6] predicts that the sandy- sediment frequency-dependent attenuation should be quadratic, α(f) =α(fo)(f / fo)n with n = 2; however the observed dependence was n = 1.8 ? 0.2 . Thus the long-range goal was to develop a simplified theory of sediment attenuation [7] verified by measurements that could explain this dependence and be applied to ocean sediments.

15. SUBJECT TERMS

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WORK COMPLETED

Numerical studies have shown factors such as rough surface scattering and anomalous sound speed perturbations due to internal waves cannot explain this inferred frequency dependence of intrinsic attenuation. To further examine this finding, shallow water, SW, transmission experiments were conducted in the Nantucket Sound [8,9] where surface roughness and internal waves were not factors in the determination of the transmission loss. The transmission loss,TL, was measured for frequencies between 220 and 1228 Hz in a nominal water depth of 13-14 m to ranges of 3600 m. The propagation path was over a fairly constant depth sandy-silty bottom protected on the north and west by Tuckernuck Shoal and on the south and east by Nantucket. [8: Fig.1] The sediment in the upper layers of the bottom was 97% sand, 3% silt, 49% porosity and density 1.7 g/cm^3. Sound speed, attenuation, and density profiles as a function of depth were determined based on these average bottom properties. The sound speed in the water was measured using a sound speed, temperature, and depth probe on the ship as well as one on board the vehicle, to be 1467±0.25 m/ s and constant over depth. The sound speed profile in the sediment increased from 1550 m/s to 1800 m/s with a gradient consistent with Hamilton's empirical relations. Density was considered to be a constant over depth to the acoustic basement, as the small gradient predicted by theory would not be influential at the frequencies employed in this experiment. [9: Fig.2; 9: 179-186] Comparison of measured range averaged TL with fast field, normal mode and parabolic equation, PE, calculations using simplified geo-acoustic profiles were excellent [9: 187-189] when a nonlinear frequency dependent attenuation was employed. The 1228 Hz TL determined the reference attenuation. An iterative comparison between range dependent PE calculations yielded a most probable value of the power exponent, $n = 1.87$, and the 95% confidence interval $1.74 < n < 2.04$ with $0.261 < \alpha(f_o = 1228) < 0.273$ in the first 5.5 m of the sediment. While this value is consistent with Biot at the upper end of the confidence interval, $n = 1.87$ provides the least bias between calculated and measured estimates.

The measurement of the bottom and sub-bottom with at frequencies of 33 and 200 kHz indicated that the roughness, layering and range dependence were not significant in this experiment. The remaining factor to be considered was shear wave conversion. An analytical treatment of a waveguide with a water layer (ρ, c) over a sediment (ρ_b, c_b) with a slow shear wave speed ($c_s < c < c_b$) shows that the rate of energy conversion to shear waves could explain the apparent additional attenuation, $\alpha_a(f) = \alpha_{swc} + \alpha_i(f)$. Here α_{swc} describes the removal of energy from the water borne field by shear waves. At higher frequencies $(\alpha_a(f) \approx \alpha_i(f))$ while at lower frequencies $(\alpha_a(f) \approx \alpha_{swc})$, thus the observed effective attenuation is determined by a power law relationship between these asymptotes with a less than quadratic dependence. This effective shear wave attenuation can be shown to be proportional to the cube of the shear wave speed, c_s^3. [11] Hamilton [10] and Stoll [2] report shear wave speeds between 100 to 300 m/s for sandy sediments with porosities of 40-50%. Hastrup [12:121-127] reports empirical relationships that relative speed ratios $1.0 \le c_b / c \le 1.079$ yield shear wave speeds $184 \le c_s \le 400\ m/s$. While the actual value of the shear wave speed and gradients in the first 5.5 m of sediments are largely unknown, these estimates indicate that the attenuation due to shear wave conversion can vary by a factor of 64. The importance of shear wave conversion in bottom reflection has been treated by Hastrup [12] while the depth dependent properties were investigated by Chapman and Godin [13].

In the analysis of the TL a comparison was made with calculations with a water iso-speed layer over a fluid half space with constant properties. The attenuation was allowed to have the power law frequency

dependence with the resulting inferred value of $n = 1.7$. Although this simplest of geoacoustic models provides a qualitative comparison with measurement and insight with respect to the modal variations; it does not capture the requisite geoacoustic characteristics. With this in mind calculations were performed on this problem with a solid bottom and a frequency dependent attenuation. A normal mode code based on Ivansson and Karasalo [14] was used to compute TL for this case at four frequencies: 125, 250, 500 and 1000 Hz. The source and receiver depths are both 6 m. The water layer was 13 m deep with a sound speed of 1467.5 m/s. The bottom half-space has a compressional speed of 1620 m/s, a density of 1.7 gm/cm^3 and attenuation: $\alpha_i(f_o)(f/f_o)^2$ with $\alpha_i(1\,kHz) = 0.30\ dB/m$. The sediment half-space was treated as a solid, $c_s = 300 m/s$, or a fluid, $c_s = 0\, m/s$. The TL, with cylindrical spreading removed, was intensity averaged over the range interval 2-10 km using a 0.2 km sliding window. The intensity averaged TL was fitted with a straight line. The range averaged TL $< TL(f,r) >_{0.2\,km}$, is shown in Fig. 1. These computational results show the importance of shear wave conversion at the lower frequencies and negligible effects at the higher frequencies. That is at a frequency of one kHz the solid and fluid bottom (dashed line) cases produce indistinguishable results; while at the frequencies of 125 and 250 Hz a large difference is observed. One must keep in mind that the attenuation due shear wave conversion, α_{swc}, is proportional to c_s^3 and consequently these results could change dramatically with the value chosen and its variation with depth. These results show that basic inversions that employ compressional effects may produce estimates of $n < 2$.

An example of this effect is shown in Fig. 2 where a comparison of the $< TL(f,r) >_{0.2\,km}$ is shown between a solid bottom (solid line) with $c_s = 300\ m/s$ with $n = 2$. and a fluid bottom (dashed line) . The $\alpha(f_0 = 1\ kHz)$ [dB/m] was chosen based on the measured results and common to all these calculations. The iterative comparison technique was employed between the solid and fluid case to determine the best fit value of $n = 1.6$. The consequence of this analysis is that inversions that employ fluid bottoms will even under the simplest of conditions yield a frequency dependence determined by the relative importance of α_{swc} and $\alpha_i(f)$. Gradients, realistic layering and other depth variations further complicate this situation. Nevertheless it is possible to quantify the attenuation, $\alpha_a = \alpha_{wc}(f,z) + \alpha_i(f,z)$, and to represent the attenuation as $\alpha_a = \alpha_i(f_o)(f/f_o)^m$ where m is a specific power exponent to compensate for shear in fluid bottom calculations.

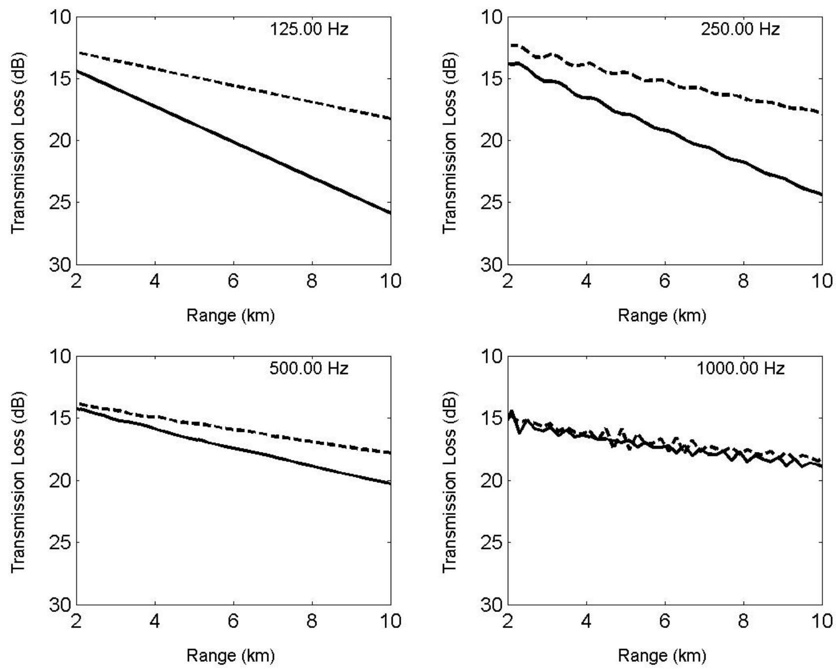

Figure 1: A comparison of cylindrically corrected range averaged transmission loss, $< TL(f, r) >_{0.2\,km}$, for frequencies of 125, 250, 500, and 1000 Hz. Calculations are presented for elastic, $c_s = 300\ m/s$, solid line and fluid, $c_s = 0\ m/s$, bottoms.

RESULTS

Sandy/silty marine sediments are water saturated and consist of diverse tiny rock pebbles. The weight of higher pebbles holds lower pebbles in contact. For low frequency acoustic disturbances, the no-slip condition and viscosity cause the local water displacement near solid surfaces to be nearly the same as that of the neighboring pebbles. Water further from surfaces oscillates relative to solid matter because of mass density difference, andviscosity limits the oscillation amplitude. Derived dissipative wave equation predicts attenuation proportional to frequency squared, proportional to the square of the difference of the densities, and inversely proportional to viscosity [15].

SW TL measurements yield intrinsic attenuation estimates for acoustic waves in the underlying sediment, with results that are consistent with attenuation being proportional to frequency raised to a power n, with n between 1.6 and 1.87. Plausible theory [7, 15] suggests n should be identically 2. The discrepancy can be explained, because the inverse analysis inferences were made with the neglect of an additional attenuation mechanism where generated lower velocity shear waves carry energy downwards out of the waveguide. The shear wave effect has a weaker dependence on frequency than the intrinsic attenuation, so the apparent exponent is shifted downward [16].

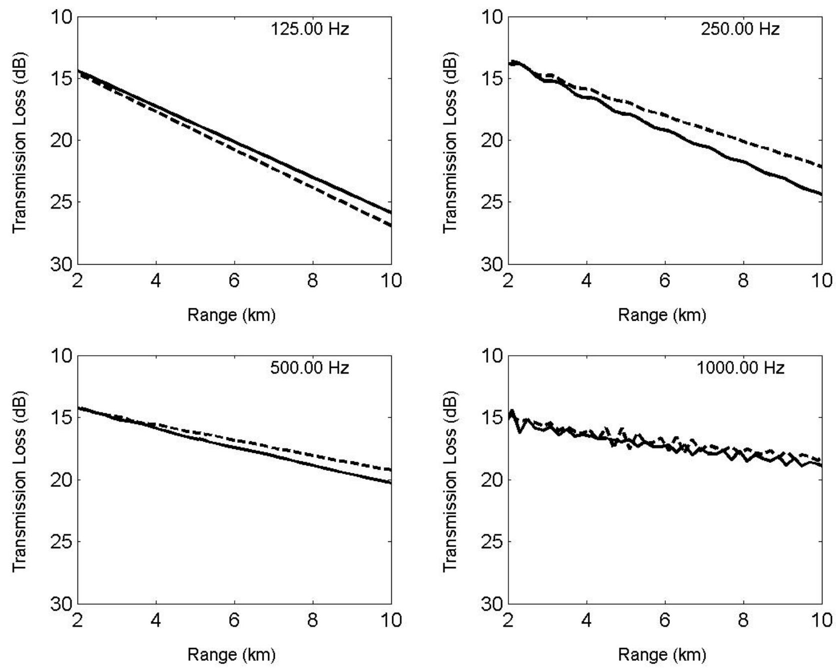

Figure 2: A comparison of cylindrically corrected range averaged transmission loss, $< TL(f,r) >_{0.2\,km}$***, for frequencies of 125, 250, 500, and 1000 Hz. Calculations are presented for solid bottom (***$c_s = 300\ m/s$***,*** $n = 2$***) case, solid line and fluid bottom (***$c_s = 0\ m/s$***,*** $n = 1.6$***) case, dashed line.***

IMPACT/APPLICATIONS

The autonomous-vehicle towed-array system is an accurate, cost-effective, and efficient measurement tool will have an impact on the cost of experiments. The physical justification for the use of a site specific nonlinear attenuation factor will impact the current bottom loss models by provide a rational for the use of these factors.

RELATED PROJECTS

The results of this research have the potential for dramatically improving the use of geo-acoustic models to accurately predict the propagation and dispersion of sound at the low frequencies (~100 Hz) to the high frequencies (~10 kHz). This effort is related to ONR-OA investigations at the WHOI and the RPI and results in sharing resources and students.

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HONORS

The Pioneers of Underwater Acoustics, Silver Medal of the Acoustical Society of America was awarded in June 2007 and was received in November 2007